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Studies on the electrochemical oxidation of methanol using La_2MO_4 (M = Ni, Cu and Zn) catalysts

La_2CuO_4 (LCO) stands out by outperforming La_2NiO_4 (LNO), La_2ZnO_4 (LZO), and many reported catalysts in methanol oxidation, offering higher activity, lower onset potential, and strong CO tolerance. Its unique electronic structure ensures superior efficiency and stability, making it a promising candidate for clean energy technologies.

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Studies on the electrochemical oxidation of methanol using La_2MO_4 (M = Ni, Cu and Zn) catalysts

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Catalytic electrochemical oxidation of methanol is emerging as a promising alternative for clean energy production. Hence, the present investigation explores the methanol oxidation reaction (MOR) using three rare-earth metal-based oxide catalysts, La_2NiO_4 (LNO), La_2CuO_4 (LCO), and La_2ZnO_4 (LZO) —synthesized via a sustainable sol-gel method. Detailed characterization through various spectroscopic techniques confirms the successful synthesis of the catalysts with distinct crystalline phases and uniform microstructures. Electrochemical analysis reveals that the LCO exhibits superior MOR activity, compared to LNO and LZO catalysts, which is further supported by density functional theory (DFT) calculations. LCO exhibits a lower Tafel slope (42 mV dec^{-1}) than LNO (220 mV dec^{-1}) and LZO (233 mV dec^{-1}). The most favourable pathway of oxidation of methanol using the LCO catalyst primarily involves C–H bond dissociation. The anti-poisoning effect of the LCO catalyst, confirmed by CO stripping analysis, ^{13}C NMR, ^1H NMR, and FTIR spectroscopy, demonstrates its strong resistance to CO poisoning and high catalytic efficiency, highlighting its potential as a promising catalyst for renewable energy applications.

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Introduction

The methanol oxidation reaction (MOR) is a benchmark electrochemical process for studying the interaction of small organic molecules with metal-based electrocatalysts, offering insight into reaction pathways relevant to energy conversion.^{1–4} The process yields valuable intermediates like formic acid, formaldehyde, and CO_2 , indicating its mechanistic complexity. Among electrocatalysts, platinum (Pt) has been widely studied due to its superior activity and selectivity.^{5–16} However, Pt-based systems suffer from severe drawbacks, including susceptibility to CO poisoning due to strong CO adsorption, high cost, limited abundance, and poor long-term stability.^{5–16} These challenges hinder their practical deployment in direct methanol fuel cells (DMFCs).^{3,17,18}

Recent efforts have focused on rare-earth-based materials, particularly those combining lanthanides with late 3d transition metals (TMs) such as Mn, Fe, Co, Ni, Cu, or Zn.^{19–27} These materials offer promising features, including tunable redox chemistry, structural flexibility, high oxygen

mobility, and enhanced corrosion resistance.^{19–27} Despite their chemical inertness stemming from 4f orbitals shielded by 5s and 5p orbitals, rare earth elements play a pivotal role in electrocatalysis. Lanthanum-based materials, in particular, stand out for their versatility, finding use in organic catalysis, electrochemical electrodes, and propellant enhancement owing to their variable occupation in f-orbital and its interaction.^{28–36} Among them, lanthanum-based oxides have attracted increasing attention due to their unique A_2BO_4 -type structures and potential for oxygen intercalation, which can significantly enhance electronic conductivity and catalytic behavior.^{37,38} For instance, La_2CuO_4 (LCO) has shown superconductivity and fast oxygen transport properties, while La_2NiO_4 (LNO) exhibits superior mixed ionic–electronic conductivity. La_2ZnO_4 (LZO), though less explored, has shown promise as a redox-active material.^{39–45}

Lanthanum-based materials have been widely studied across various catalytic and electronic applications. However, studies on comprehensive investigations of their use as electrocatalysts for methanol oxidation and reaction mechanism pathways remain limited.^{25,46–50} Recent studies have shown that MOR activity is highly influenced by the type of the transition metal atom within the oxide framework. Substituting different 3d metals not only alters the electronic structure but also impacts surface adsorption, reaction kinetics, and overall efficiency.^{25,46–50} Despite progress, the precise role of the transition metal in governing catalytic

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behavior, as well as the contribution of the rare-earth element (La^{3+}), remains underexplored. Additionally, the oxidation states of metal ions are critical in determining catalytic activity. Deviations from ideal stoichiometry due to oxygen vacancies or excess can significantly affect charge transport properties and surface reactivity.⁵¹ This redox flexibility influences intermediate binding strengths and, consequently, both activity and selectivity in the MOR. A major challenge in the MOR is CO poisoning, where strongly adsorbed CO intermediates deactivate the active sites and limit long-term stability. Furthermore, while La-based mixed metal oxide has been hypothesized to show enhanced CO tolerance due to its redox flexibility and surface oxygen dynamics, direct validation in the context of MOR is still sparse.

To address these gaps, this study systematically investigates La_2MO_4 ($M = \text{Ni}, \text{Cu}, \text{Zn}$) catalysts for the MOR using a combined experimental and theoretical approach. The catalysts were synthesized *via* a facile sol-gel method and comprehensively characterized by powder X-ray diffraction (PXRD), field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), and high-resolution transmission electron microscopy (HRTEM). Electrochemical performance was assessed *via* cyclic voltammetry (CV), with LCO demonstrating superior MOR activity compared to LNO and LZO. Among the series, LCO exhibited the most promising performance, with a lower onset potential (~ 1.15 V *vs.* RHE) and reduced Tafel slope compared to LNO and LZO. Density functional theory (DFT) calculations further support the experimental findings by revealing favorable methanol adsorption energies, reaction intermediates, and pathways on LCO surfaces. The energy and k -point convergence test is provided in SI section S1B and Fig. S1. This suggests that the superior activity of LCO arises from its optimal electronic structure and higher density of active sites. Overall, this integrated study deepens the understanding of how transition metal substitution and rare-earth metal coordination govern MOR activity and stability in the considered electrocatalysts.

Results and discussion

Characterization

The LNO, LCO, and LZO catalysts were synthesized using a straightforward and sustainable sol-gel approach (Fig. 1), using standard reagents including lanthanum(III) nitrate hexahydrate ($\text{La}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$, 99%), copper(II) nitrate trihydrate ($\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, 99%), nickel(II) nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 99%), zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 99%), citric acid (CA) ($\text{HOC}(\text{COOH})(\text{CH}_2\text{COOH})_2$, 99%), and ammonia (NH_3) solution, purchased from the Sigma Aldrich. Detailed computational methodologies, synthesis protocols, and convergence details are provided in SI section S1 and Fig. 1. The sol-gel method was chosen for its simplicity, reproducibility, and ability to form a porous structure. The morphology and crystalline phases of the catalysts were examined using various spectroscopic techniques. The pictorial representation of the crystal structure for LNO, LCO, and LZO catalysts is provided in Fig. 2a-c.

The FESEM analysis provides detailed insights into the topology of the synthesized catalysts, elemental distribution, and element mapping of the crystal surfaces. The FESEM topography clearly shows that the LNO, LCO, and LZO catalysts exhibit a dense microstructure, characterized by well-grown grains approximately 100 nm in size (see Fig. 2d-f). Following the analysis of the FESEM results, we conducted an elemental mapping at 1 μm of the considered catalysts, which confirmed the presence of all anticipated elements in the samples. The EDS results display the characteristic peaks and atomic ratios associated with the elements, as shown in Fig. 2d-f, and the SI (section S2 and Fig. S2), which further confirm the formation of synthesized materials.

PXRD analysis was conducted to determine the crystalline structure and phase purity of the synthesized LNO, LCO, and LZO catalysts. Rietveld refinement was performed by systematically adjusting parameters using GSAS II software.⁵² The PXRD pattern of LNO, shown in Fig. 2g, displays well-defined peaks at $2\theta = 30.9^\circ, 40.3^\circ, 44.3^\circ, 51.6^\circ, 58.3^\circ, 67.4^\circ,$ and 78.8° , corresponding to the (111), (120), (121), (202),

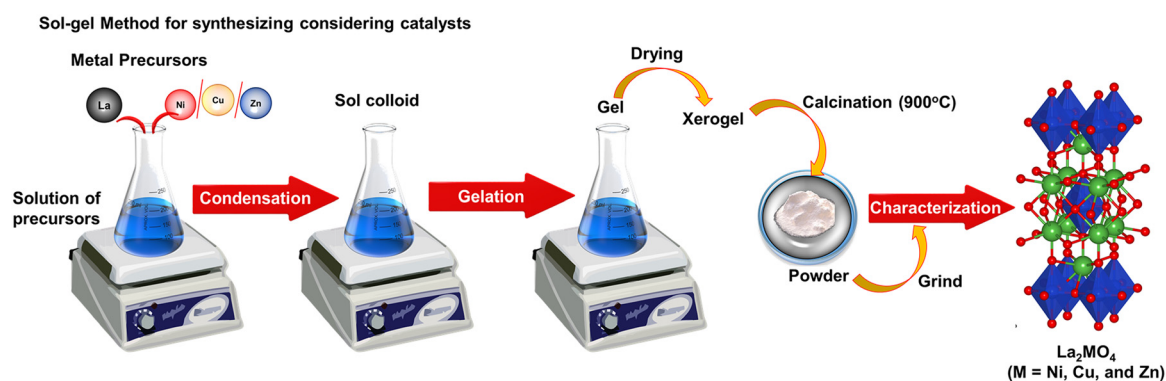


Fig. 1 Schematic representation of the La_2MO_4 synthesis process. Color code: red: oxygen, green: lanthanum, and blue polyhedral represents the position of metal atom M.





Fig. 2 Optimized supercell cell of (a) LNO, (b) LCO, and (c) LZO; FESEM image of (d) LNO, (e) LCO, and (f) LZO; and PXRD plot of (g) LNO, (h) LCO, and (i) LZO. Color code: red: oxygen, green: lanthanum, grey: nickel, blue: copper, and black: zinc.

(310), (302), and (322) planes, respectively, as referenced in PDF#34-0984. Additional reflections are observed at 24.0° (101), 32.7° (110), 42.7° (105), 43.7° (114), 56.3° (204), and 63.6° (206), aligning well with the tetragonal phase of La_2NiO_4 (space group $I4/mmm$), as referenced in PDF#80-1346. These results confirm the successful synthesis of a single-phase, highly crystalline LNO material, in agreement with previous literature reports.^{53–58}

For LCO, the PXRD profile (Fig. 2h) exhibits intense diffraction peaks at $2\theta = 24.3^\circ$, 27.1° , 31.1° , 33.1° , 33.4° , 41.2° , 41.7° , 43.5° , 47.8° , 54.0° , 54.4° , 55.8° , 58.0° , 64.9° , 65.1° , 69.6° , 70.0° , 75.3° , 76.5° , and 78.5° corresponding crystallographic planes (111), (004), (113), (020), (200), (006), (115), (204), (220), (206), (117), (224), (133), (226), (135), (040), (400), (331), (228), and (333). The diffraction pattern corresponds closely with the standard orthorhombic phase of La_2CuO_4 (PDF#82-2142, space group $Bmab$), confirming the formation of a phase-pure LCO perovskite upon calcination at 900°C for 2 h. A few minor peaks at $2\theta = 35.9^\circ$, 38.9° , and 49.1° were also detected, indicative of a trace CuO phase (PDF#80-1917), suggesting slight phase segregation during synthesis. Nonetheless, the dominant phase remains orthorhombic La_2CuO_4 with high

crystallinity and structural integrity, consistent with previous findings.^{59–63}

The PXRD pattern for the LZO catalyst (Fig. 2i) reveals diffraction peaks attributable to a mixed oxide system of La and Zn. Notable peaks at $2\theta = 31.0^\circ$ (101) and 36.0° (100) are consistent with overlapping reflections from both La- and Zn-based oxides. Additional diffraction features at 40.0° (101), 42.3° (100), 51.0° (101), and 55.0° (111) further confirm the formation of a homogeneous La–Zn oxide composite.^{64–66}

Notably, no diffraction peaks corresponding to La_2O_3 , such as (100) at 15.7° and (211) at 48.8° , were observed,⁶⁷ affirming the absence of unreacted lanthanum oxide in LCO, LNO and LZO catalysts as shown in SI section S3 and Fig. S3a.

The XPS was employed to investigate the surface chemical composition and electronic structure of the LNO, LCO, and LZO catalysts, offering valuable insights into their surface properties. The surface composition, fitting results, and binding energies of each element present in LNO, LCO, and LZO catalysts are presented in the SI (section S3 and Tables S1a–d). Fig. 3a(i–iii) shows the O 1s, Ni 2p and La 3d XPS spectra for the LNO catalyst. The O 1s spectrum was deconvoluted into distinct peaks, with the peak at 530.6 eV





Fig. 3 XPS analysis of (a) LNO, (b) LCO, and (c) LZO catalysts (where (i) O 1s, (ii) transition metal 2p (Ni, Cu, Zn), and (iii) La 3d core levels, respectively).

indicating oxygen in the Ni–O bond. The La–O bond is ionic, while the Ni–O bond is covalent. The high-resolution Ni 2p spectrum of the LNO sample displays prominent peaks of Ni 2p_{3/2} and Ni 2p_{1/2}. Additionally, the high-resolution La 3d spectrum reveals four distinct peaks at 834.65 eV, 838.35 eV, 851.15 eV, and 855.01 eV, corresponding to La 3d_{5/2} and La 3d_{3/2}, indicating the presence of La³⁺. However, due to the presence of significant overlapping between the Ni 2p_{3/2} and La 3d_{3/2} satellite peaks of Ni 2p and La 3d, the core-level spectra of La 3d and Ni 2p were not analyzed further.

Similarly, Fig. 3b(i) shows that the peak around 529.00 eV in the O 1s spectra corresponds to oxygen in the La–O bond for the LCO catalyst. The La 3d spectra exhibit two doublets due to spin–orbital splitting, with main peaks at 835.48 eV and 852.44 eV, and satellite peaks at 838.48 eV and 856.17 eV, assigned to La 3d_{5/2} and 3d_{3/2}, respectively (Fig. 3b(iii)). The Cu 2p spectrum (Fig. 3b(ii)) reveals two components at binding energies of 933.42 eV (Cu 2p_{3/2}) and 954.74 eV (Cu

2p_{1/2}), with a peak separation of 20.9 eV, confirming the presence of Cu²⁺. The peaks at 940.28 eV, 942.07 eV, and 963.00 eV are attributed to the oscillation of the Cu²⁺ structure consisting of different kinds of spin–orbit lines, called SP-1, SP-2, and SP-3, respectively. The La 3d and Cu 2p spectra confirm the presence of only La³⁺ and Cu²⁺ on the LCO surface. XPS analysis for the LCO catalyst is also provided in the SI (section S3 and Fig. S3b).

The XPS spectrum for the LZO catalyst is provided in Fig. 3c(i–iii). In the O 1s spectrum, the peak at 529.0 eV indicates oxygen in the Zn–O bond, while the peak at 531.06 eV corresponds to oxygen in the La–O bond. The peaks at 834.47 eV and 855.47 eV are assigned to La 3d_{5/2} and La 3d_{3/2}, respectively, characteristic of La³⁺. The Zn 2p spectrum shows peaks at 1021.89 eV and 1045.00 eV, corresponding to Zn²⁺ (Zn 2p_{3/2} and Zn 2p_{1/2}). The La 3d peaks for LNO, LCO, and LZO are observed between 830–851 eV and 837–855 eV for 3d_{5/2} and 3d_{3/2}, respectively, indicating La³⁺. Additionally,



lower binding energy peaks (527–530 eV) in the O 1s spectrum correspond to stoichiometric O²⁻, while lattice oxygen is indicated by peaks at ~528.5 and ~530.3 eV. The binding energy at ~531.1 eV suggests the presence adsorbed oxygen.

The FTIR analysis of the LMO catalyst revealed the formation of La₂MO₄ which is also supported by PXRD and XPS analysis. The detailed discussion of the various FTIR stretching frequencies of the metal oxide is provided in the SI (section S4 and Fig. S4). The FTIR spectra reveal peaks at higher wavenumbers that are related to hydrogen and oxygen bonds. The peak observed in the range of 500–600 cm⁻¹ typically corresponds to metal–oxygen (M–O) stretching vibrations, which are characteristic of the A₂BO₄-type structure.^{65,68–72} The peak at 653–679 cm⁻¹ is attributed to the La–O stretching vibration along the *c*-axis, while the 503–523 cm⁻¹ band is assigned to the Ni–O stretching vibration.

The chemical structure of the LCO binary oxide was further examined using FTIR spectroscopy.^{68,71,72} The low-intensity bands observed at 502 and 1065 cm⁻¹, as well as at 591 and 1108 cm⁻¹, are associated with Cu–O and La–O stretching modes, respectively, which are characteristic of the orthorhombic LCO phase. Additionally, the presence of bands at 596 and 1187 cm⁻¹, corresponding to Cu–O stretching modes, in all the samples indicates the formation of Cu–O as a secondary phase. This is likely due to the 1:1 precursor ratio used, resulting in the formation of an A₂BO₄-type structure.^{69,70} Similarly, the FTIR spectrum of the LZO catalyst exhibits characteristic peaks at 529.4 and 1479 cm⁻¹, which are attributed to Zn–O stretching vibrations. A distinct peak at 609 cm⁻¹ further supports the presence of intrinsic Zn–O stretching. Moreover, the broad peak observed in the range of 450–550 cm⁻¹ is often associated with bridging vibrations or bending modes involving both La and Zn



Fig. 4 (a) N₂ adsorption and desorption isotherms, along with the (insets) pore size distribution graph, (b) CVs in 0.5 M H₂SO₄ at 100 mV s⁻¹ vs. RHE, CVs for the MOR in (c) 0.5 M H₂SO₄ + 0.5 M CH₃OH solution at a scan rate of 50 mV s⁻¹ versus the RHE, and (d) 0.5 M H₂SO₄ + 0.5 M CH₃OH solution at a scan rate of 20 mV s⁻¹ versus the RHE, (e) LSV curve at 0.5 M H₂SO₄ + 0.5 M CH₃OH solution at a scan rate of 50 mV s⁻¹ versus the RHE, (f) Tafel plot, (g) Nyquist plot, (h) chronoamperometry (*I*-*t*) curve, and (i) CVs in 0.5 M H₂SO₄ + 0.5 M CH₃OH solution at a scan rate of 100 mV s⁻¹.



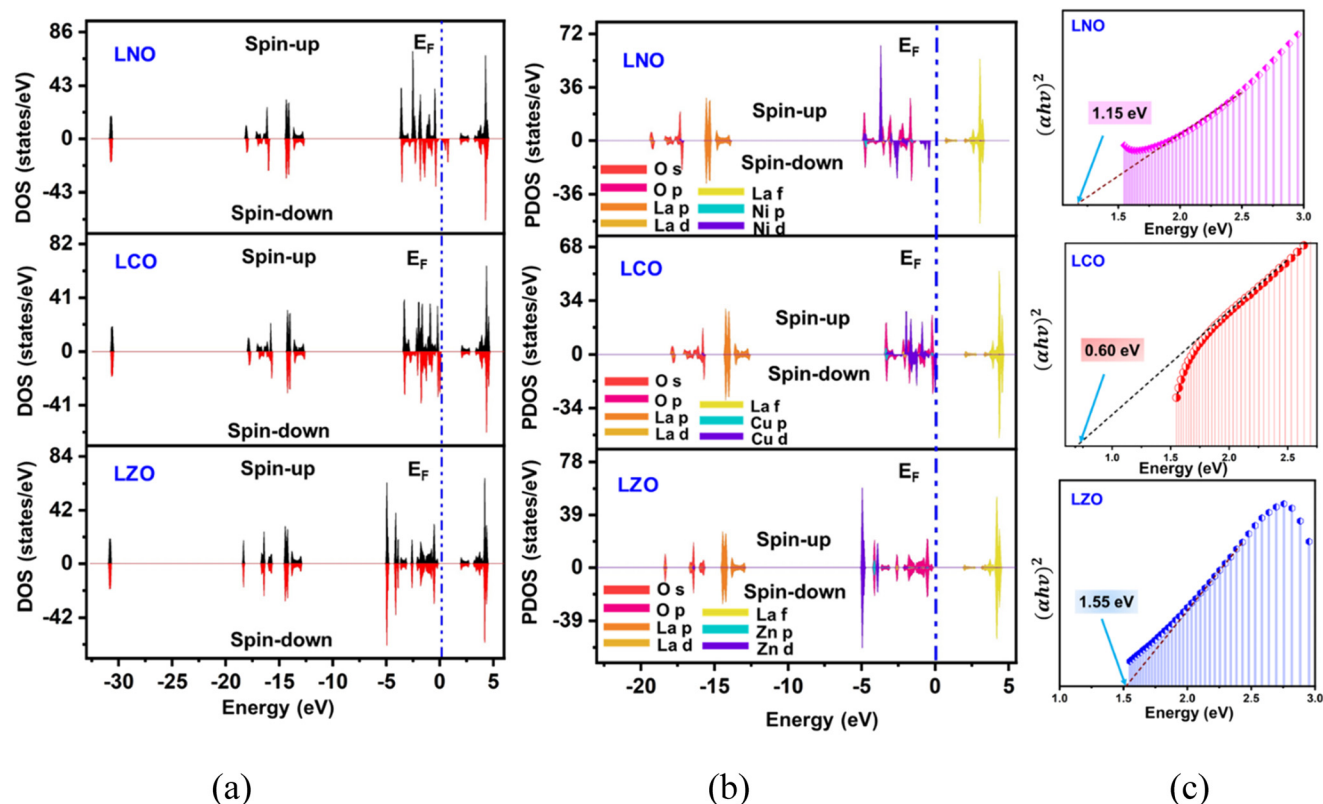


Fig. 5 Calculated (a) total density of state, (b) projected density of state, and (c) Tauc plot for the considered catalysts.

Analysis of the PDOS (Fig. 5) reveals that in the LNO catalyst, the interaction between O 2p and Ni 3d states is primarily localized between -0.69 and -4.83 eV. For the LCO and LZO catalysts, the interaction between O 2p and Cu/Zn 3d states is mainly localized between -0.08 to -3.31 and -0.31 to -5.06 eV, respectively. Notably, strong interactions between Cu 3d states and O 2p states are observed from -0.08 to -1.30 eV. In contrast, the interactions between Ni and Zn 3d states and O 2p states are minimal at the Fermi level (E_F) for LNO and LZO.

In the LMO catalysts, where M represents Ni, Cu, or Zn, the incorporation of different metal ions leads to the splitting of the d orbitals into t_{2g} and e_g states. This splitting results in a valence band below the Fermi level, comprising the occupied M t_{2g} and e_g orbitals, as well as O 2p orbitals, while the unoccupied e_g orbitals above the Fermi level contribute to the conduction band. The calculated band gaps at the Γ point are 0.30 eV for LNO and 2.09 eV for LZO, whereas the experimental values are 1.15 and 1.55 eV, respectively. The DOS and PDOS analysis for LCO predicts the electron density at the Fermi level; however, the Tauc plot yields a lower band gap value of 0.60 eV. The PBE method tends to overestimate the band gap, resulting in a small discrepancy between theoretical and experimental values for LNO, LCO, and LZO.

The high electrocatalytic performance of LCO in the MOR can be attributed to several factors. One critical aspect is its distinct morphology, which enhances MOR performance by facilitating ion and mass transport both within the catalyst

structure and at the electrode–electrolyte interface. Another contributing reason is its exceptional electronic conductivity, which arises from the synergistic interaction between Cu and O atoms, resulting in reduced charge transfer resistance. The narrow band gap of LCO imparts metallic properties, facilitating the movement of electrons from the valence band to the conduction band. Significant overlap between the t_{2g} and e_g orbitals of Cu^{2+} and the O 2p orbitals within the valence band is observed, likely due to the proximity of Cu^{2+} (3d states with e_g symmetry) to the equatorial oxygen atoms.^{79–84} This enhances the covalency between Cu 3d and O 2p orbitals, leading to band hybridization and potential pinning of the Fermi level at the top of the O 2p band.^{79–84} This pinning significantly affects the stability of lattice oxygen in LCO oxides, making them more prone to oxidation.^{79–84} Furthermore, the DOS and PDOS analysis of the LCO catalyst reveals that the bonding and antibonding orbitals near the Fermi level are primarily concentrated on the surface Cu and O sites, indicating high electroactivity. A gap state was also identified near the La and O sites. The La orbitals contribute mainly to the conduction band, and the combined contributions of La, Cu, and O to the gap state help lower the electron transfer barrier. The observation of electron density at the Fermi level further supports the efficient electron transfer during the reaction. Furthermore, the enhanced covalency in LCO contributes to its superior catalytic activity compared to LNO and LZO, as supported by the CV analysis. Overall, the metallic characteristics of LCO



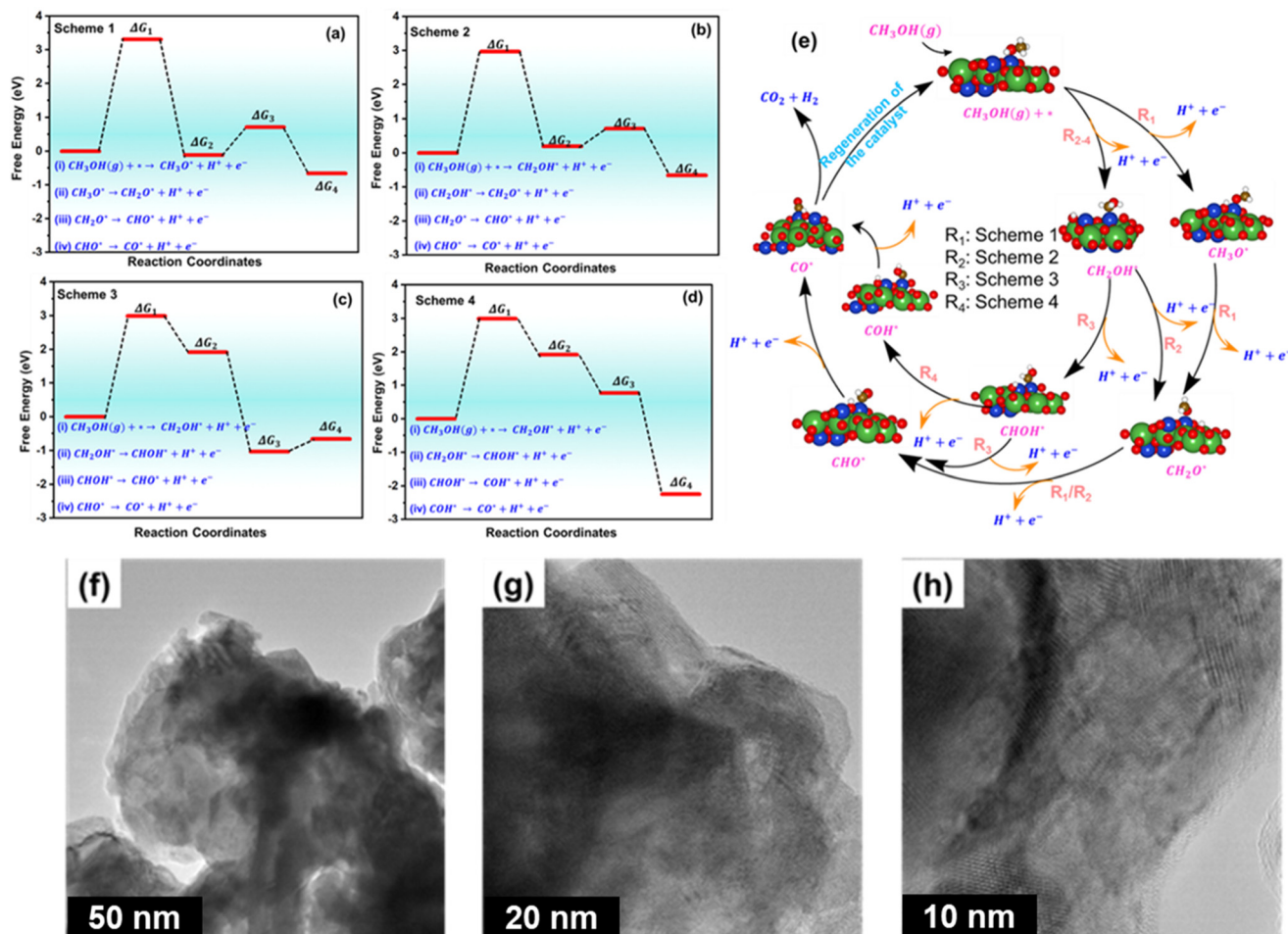
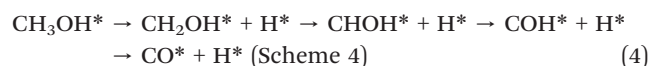
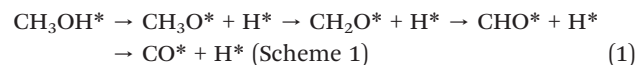


Fig. 6 Schematic representation of the (a)–(e) free energy diagram for the MOR using different mechanistic schemes. The * represents the active surface of the LCO catalyst. (f)–(h) HRTEM image of the LCO catalyst at different resolutions. Color code: red: oxygen, green: lanthanum, grey: nickel, blue: copper, black: zinc, white: hydrogen, and brown: carbon.

result in the lowest charge-transfer resistance and highest electronic conductivity among the catalysts. However, elucidating the methanol oxidation mechanism on the LCO surface through experimental analysis remains challenging. Thus, to unravel the reaction mechanism occurring on the surface of the LCO catalyst, DFT calculations were conducted. The detailed mechanism of methanol oxidation over the LCO catalyst is depicted in Fig. 6.

Reaction mechanism

Based on the experimental analysis, LCO has been identified as a promising catalyst for the MOR. This section explores how different intermediates are adsorbed during the electrochemical oxidation of methanol.^{78,85} To elucidate the complete MOR mechanism, various potential elementary reactions were evaluated. Methanol dehydrogenation into CO* and H* on the LCO surface is considered to proceed through four distinct pathways. These pathways are systematically summarized in eqn (1)–(4) as follows:



These pathways are mainly categorized into two types: (i) initial activation of the O–H bond (Scheme 1) and (ii) initial activation of the C–H bond (Schemes 2–4). Further investigation examines the different intermediates generated from the dissociation of CH₃OH, as illustrated in Fig. 6 and the SI (section S12 and Fig. S14a).

Scheme 1 outlines a pathway where oxidation begins with the dissociation of the O–H bond in methanol, followed by the removal of one, two, and three hydrogen



atoms from the methyl group to yield CO. Scheme 2 starts with the removal of the first hydrogen atom from the methyl group of methanol (CH₃OH), followed by the sequential removal of hydrogen atoms from the hydroxyl group and the second and third hydrogen atoms from the methyl group. Scheme 3 describes the removal of two hydrogen atoms (the first and second) from the methyl group of CH₃OH, followed by the sequential removal of a hydrogen atom from the hydroxyl group and the third hydrogen atom from the C-atom. Finally, Scheme 4 involves the sequential removal of all three hydrogen atoms from the C-atom, followed by the removal of a hydrogen atom from the hydroxyl group of CH₃OH. A detailed discussion of these reaction pathways is provided in the SI (section S12 and Fig. S14).

Fig. 6 illustrates the adsorbed intermediates on the LCO surface. The analysis reveals that the Cu site is the most favourable for CH₃OH adsorption due to the availability of the Cu-d orbital at the Fermi level, which facilitates CH₃OH oxidation. Consequently, the theoretical analysis focuses on the Cu site for the MOR. Fig. 6f–h presents the HRTEM topography of LCO at different resolutions.

The methanol oxidation can proceed *via* the dissociation of either the C–H or O–H bond, differentiating the pathway outlined in Scheme 1 from those in Schemes 2–4, as mentioned above. Preliminary experimental and theoretical results suggest that the LCO catalyst is particularly effective for the MOR *via* Scheme 3, which involves C–H bond dissociation. In contrast, Schemes 1 and 2 exhibit weaker binding of intermediates, leading to their exclusion from optimal pathways. Both Schemes 3 and 4 demonstrate a strong interaction of LCO with intermediates, making them feasible due to their favourable energy profiles. However, Scheme 4 shows strong CO adsorption, resulting in a more negative Gibbs free energy and subsequent CO poisoning. Conversely, Scheme 3 exhibits weaker CO binding (Gibbs free energy of –0.66 eV), allowing CO to desorb from the LCO catalyst surface with minimal energy input. Therefore, Scheme 3 emerges as the most efficient pathway among the feasible routes.

To gain a deeper understanding of the influence of various adsorption intermediates on the LCO catalyst, crystal orbital Hamilton population (COHP) analyses were conducted as shown in the SI (section S12 and Fig. S14b). The spin-polarized COHP plots for α - and β -spin electrons in all adsorbed intermediates on the LCO catalyst are presented in the SI (section S12 and Fig. S14b). The COHP analysis reveals that bonding contributions are represented by negative values (right), while anti-bonding contributions are indicated by positive values (left). Compared to CH₃O adsorbed on the LCO catalyst, CH₂OH demonstrates a reduced anti-bonding orbital population, leading to an increase in the binding strength of this intermediate. Similarly, the CHO intermediate exhibits a decrease in anti-bonding orbital population compared to

the COH intermediate. Integral COHP (ICOHP) values further corroborate the adsorption behaviour of intermediates on the LCO catalyst surface. The ICOHP values for all types of intermediates adsorbed on LCO are provided in the SI (section S12 and Table S2). Orbital interactions, particularly between 3d(Cu)–2p(C) and 3d(Cu)–2p(O), play a crucial role in the MOR. The ICOHP values indicate that the 3d(Cu)–2p(C) bonding interaction in the CHO adsorbed intermediate (–2.40 eV) is stronger than the 3d(Cu)–2p(O) interaction (–1.33 eV), which further validates the C–H activation being more preferable than C–O activation.

To gain deeper insight into the reaction mechanism and role of the Cu atom in electrooxidation at each stage of the reaction, DOS and differential charge density analyses ($\rho(C_{\text{LCO-intermediate}}) - \rho(\text{intermediate}) - \rho(C_{\text{LCO}})$) were performed (see SI section S14 and Fig. S14c and d). Results show that the Cu 3d orbital at the Fermi level reduces the number of anti-bonding states below the Fermi level, highlighting the strong adsorption capability of LCO for adsorbate molecules. The electron density at the Fermi level across all intermediates suggests efficient electron transfer and robust adsorption of intermediates on the LCO catalyst. Details on the orbital interactions between LCO and the intermediates are provided in SI section S12. Charge density difference plots for the most plausible reaction pathway (Scheme 3) show a significant increase in localized charge density at the LCO–intermediate interface, indicating strong interactions. This redistribution of charge reveals that metallic Cu covalently interacts with the active site of the intermediates. Electrons accumulate at the intermediates' active site and are depleted around the Cu atom of the LCO catalyst, as shown in the cyan and yellow areas in SI section S12 and Fig. S14d. These results are consistent with experimental findings and contribute to the improved electrical conductivity, as confirmed by the DOS calculations.

The comparison of MOR performances on the LCO catalyst with and without oxygen defects is also considered in the present investigation. The detailed analysis is provided in SI section S13 and Fig. S15. The calculated relative Gibbs free energies are provided in SI section S13 and Table S3. Calculated results clearly indicate that Scheme 3 is thermodynamically preferred for the MOR activity on the LCO surface without oxygen defects, compared to its defective counterpart. However, intrinsic oxygen vacancies in Ln-based metal oxides are known to enhance oxygen mobility and improve the kinetics of catalysis.^{86,87} Despite this, the weaker adsorption of CHO species on the oxygen-deficient LCO surface further limits its catalytic efficiency. Therefore, based on the energy profiles and adsorption properties, Scheme 3, which represents the LCO surface without oxygen defects, emerges as the most efficient pathway among the feasible routes. Further, the comparative analysis of the LCO catalyst with other reported catalysts for the MOR are provided in SI section S14 and Table S4.



Conclusions

This study explores the electrocatalytic performance of lanthanum-based metal oxide catalysts, LNO, LCO, and LZO for methanol oxidation reactions (MORs), forecasting the LCO as the most promising catalyst for clean energy production. The catalysts were synthesized using a sustainable sol-gel method and characterized by PXRD, FESEM, and XPS, which confirmed their successful formation with well-defined crystalline phases and uniform microstructures. Electrochemical analysis revealed that LCO exhibited superior MOR activity compared to LNO and LZO, with a notable peak at 1.27 V *versus* RHE. These results highlight LCO's unique electronic properties, supported by DFT calculations, which indicated that the preferred methanol oxidation mechanism on LCO involves the C-H bond dissociation pathway. A key innovation of this study is the identification of LCO's exceptional anti-CO poisoning behavior. CO stripping analysis, along with ¹³C NMR, ¹H-NMR, and FTIR spectroscopy, demonstrated that CO efficiently desorbs from the LCO surface, preventing CO accumulation and mitigating poisoning effects. This behavior is crucial for maintaining the stability and activity of the catalyst during the reaction. LCO's strong interaction with intermediates and favorable energy profiles make it particularly efficient in the MOR, while also preventing CO poisoning, a major limitation in many electrocatalytic systems. The findings underscore the potential of LCO as a high-performance, sustainable catalyst for methanol oxidation, with significant implications for renewable energy applications. This work contributes valuable insights into the optimization of lanthanum-based catalysts, highlighting LCO's potential in fuel cells and other electrochemical devices.

Conflicts of interest

The authors declare no competing financial interest.

Data availability

Supplementary information: Materials and methods, energy and *k*-point convergence test, EDS analysis, XRD and XPS analysis, FTIR spectrum of LMO, electrooxidation of methanol, band structure analysis of LMO, electron localization function (ELF), elementary steps in the MOR reaction involving electron transfer, along with their corresponding reaction free energy expressions, CO-stripping curve, ¹³C NMR, ¹H-NMR, FTIR analysis after electrolysis, comparison of MOR performances on the LCO catalyst with and without oxygen defects, and comparison of MOR performances with other catalysts. See DOI: <https://doi.org/10.1039/D5CY00827A>.

All the data supporting the findings of this article are provided in the SI.

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